USC 2000-2001 ACADEMIC YEAR AEROSPACE AND MECHANICAL ENGINEERING DEPARTMENTAL SEMINAR SERIES

NANOSATELLITE DESIGN PRINCIPLES AND CONCEPTS

John L. West
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA

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BACKGROUND

- NASA's BOLD GOALS FOR SOLAR SYSTEM EXPLORATION IN THE NEW MILLENNIUM, IN CONJUNCTION WITH ANTICIPATED STEADY OR DECLINING BUDGETS, NECESSITATE NEW EMPHASIS ON LOW-COST SPACECRAFT DESIGNS TO CONTINUE THE PACE OF SCIENTIFIC DISCOVERY

- GOAL POINTS TO A RETURN TO SMALL, LOW-COST SPACECRAFT COMPARABLE IN SIZE TO THE FIRST EXPLORER SATELLITE IN 1958 BUT COMPARABLE IN CAPABILITY WITH 1990's SPACECRAFT

- WORK HEREIN EXPLORES THE SPACECRAFT SYSTEM DESIGN PRINCIPLES PERTINENT TO THE DESIGN OF SUCH SMALL, HIGHLY-CAPABLE SPACECRAFT OR "NANOSATS"

DEFINITIONS AND ASSUMPTIONS

- **SMALL SPACECRAFT DESIGN CLASSES**

CLASS	RESOURCES			COMMENTS
	MASS, KG	POWER, W	SIZE,* cm	
I	5-15	5-15	30L X 30W X 30H	JPL 2ND GENERATION MICROSPACECRAFT DESIGN REGIME
II	1	1-5	10 DIA	AEROSPACE CORP NANOSAT DESIGN REGIME
III	<<1	<1	1-3 DIA	JPL "ASPIRIN." AEROSPACE CORP PICOSAT REGIME (~ 1 gm)

* IN LAUNCH CONFIGURATION

DEFINITIONS AND ASSUMPTIONS (Cont'd)

- APPLICABLE TECHNOLOGIES
  - MICROELECTROMECHANICAL SYSTEMS (MEMS)
  - NANOTECHNOLOGY, DEFINED AS ANY NEW TECHNOLOGY THAT PERMITS A HIGH DEGREE OF MINIATURIZATION
  - OTHER PROMISING NEW TECHNOLOGIES

- CRITERIA FOR TECHNOLOGY UTILIZATION

  ENABLES:
  - LOW LIFE-CYCLE COST
  - LOW SPACECRAFT COST
  - LOW LAUNCH COST
  - LOW OPERATIONS COST
  - HIGHER RETURN PER DOLLAR
  - U.S. INNOVATION IN RESEARCH AND TECHNOLOGY

  AND:
  - SERVICES A SPACECRAFT FUNCTIONAL NEED

- TECHNOLOGY USE – OR FLIGHT – DATE
  - 2010

MEMS PRODUCTION CAPABILITIES

- BOTH DOMESTIC AND FOREIGN FABRICATION FACILITIES EXIST
- DOMESTIC FACILITIES INCLUDE UNIVERSITIES, FFRDC'S, AND BOTH FEDERALLY SUBSIDIZED AND UNSUBSIDIZED PRIVATE INDUSTRY
- MOST FACILITIES OFFER RESEARCH CAPABILITY ONLY. ONLY A FEW ADVERTISE PRODUCTION CAPABILITY
- 14 DOMESTIC AND 7 FOREIGN FACILITIES OFFERING RESEARCH CAPABILITY EXIST. 7 OF THE DOMESTIC AND 5 OF THE FOREIGN FACILITIES ADVERTISE PRODUCTION CAPABILITY
- ESTIMATED $ INVESTMENT TO CREATE A START-UP MEMS PRODUCTION FACILITY IS COMPARABLE TO THE ACTUAL COST OF A SEMICONDUCTOR CHIP PRODUCTION FACILITY IN THE EARLY '80s
  - MEMS FACILITY:

    $35 – 40 MILLION, 1995 (ESTIMATE)
  - SEMICONDUCTOR CHIP FACILITY:

    $50 – 60 MILLION, 1982 (ACTUAL)

    $1.5 BILLION, 1995 (ACTUAL, MOTOROLA)

MEMS PRODUCTION CAPABILITIES (Cont'd)

DOMESTIC

FACILITY	CAPABILITY: RESEARCH	CAPABILITY: PRODUCTION
• EG & G IC Sensors, Milpitas, CA	X	X
• Motorola, Phoenix, AZ	X	X
• Honeywell Microswitch Div, Freeport, IL	X	X
• Lucas Novasensor, Fremont, CA	X	X
• MCNC MEMS Tech Apps Center, No. Carolina	X	X
• Lawrence Livermore, EE Micro Tech Center	X	
• UCLA	X	
• Stanford U	X	
• Case Western Reserve U	X	
• MIT Microsystems Lab	X	
• Louisiana Tech, Inst for Manufacturing	X	
• U of Michigan	X	
• Northeastern U	X	

Source: ARPA, et al

FOREIGN

FACILITY	CAPABILITY: RESEARCH	CAPABILITY: PRODUCTION
• Alberta Microelectronic Ctr, Alberta, Canada	X	X
• CSEM Swiss Ctr for Electronics and Microtechnologies	X	X
• Delft U of Tech, Netherlands	X	X
• U of Durham, England	X	
• VTT Electronics, Finland	X	X
• Fraunchofer Gesellschaft, Germany	X	X
• Simon Fraser U, BC, Canada	X	

Source: ARPA, et al

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CANDIDATE MEMS/NANOTECHNOLOGIES FOR SPACECRAFT

SPACECRAFT SUBSYSTEM	TECHNOLOGY
• Telecommunications	• MEMS Telecom Filters and Oscillators • Thin-Film Patch Antenna • Millimeter Wavelength Horns and Reflector Antennas • Micromachined Wave Guides • Optically Processed Beam Forming • Optical Communications • Photonics Oscillator
• Guidance and Control	• Micro Star Tracker • Micro Sun Sensor • Micro Horizon Sensor • MEMS Reaction/Momentum Wheels • MEMS Control Moment Gyro • Micro Reaction/Momentum Wheels • Micro Control Moment Gyro Gyros • Accelerometers • Inertial Measurement Unit
• Information Processing and Control	• Si Micro-Disk Data Storage Array
• Power	• Conformal Coated/Advanced Technology Batteries • GaAs Arrays • Peak Power Tracker
• Structure/Mechanical Devices/Cabling	• Fiberoptic Positioners and Actuators • Micromechanical Switches • Micromechanical Actuators • Vibration Dampers • Advanced Composite Structures

SPACECRAFT SUBSYSTEM	TECHNOLOGY
• Propulsion	• Micro (MEMS) Valves • Doped Si Isolation Valve • MEMS Filters • Subliming Solid Thruster • Solid/Liquid/Pulsed Plasma Thrusters • Peristaltic Pumps
• Thermal Control	• Micropumps • Micro Refrigerators • Mini Louvers • Micro Louvers • MEMS Thermal Switch • Paraffin-Based Thermal Switch • Electro-Chromic Devices • Variable Emittance Coatings • Micro Heat Pumps • Micro Heat Exchangers • Micro Heat Pipes (1 mm dia) • Phase Change Composite Structures • "Button" Radioisotope Heater Unit (RHU) (<<1 W)
• Sensor	• Computed Tomography Imaging Spectrometer • Micro Opto-Chemical Sensors • Pressure • Temperature • Magnetic Field • Wind Speed • Humidity • Seismic • Chemical Contamination • Radiation (IR, EMI, ESD) • Active Pixel Sensors • Micromachined Deformable Mirrors

DESIGN RULES

- FEW DESIGN RULES EXIST TO GUIDE THE SPACECRAFT SYSTEM DESIGNER IN THE DESIGN OF SPACECRAFT BASED ON, OR UTILIZING, MEMS AND NANOTECHNOLOGY
- DESIGN ON THE SCALE OF MEMS IS DIFFICULT FOR SPACECRAFT SYSTEM DESIGNERS BECAUSE OF LACK OF EXPERIENCE IN THIS DESIGN REGIME
- MOST RULES THAT DO EXIST ARE DERIVED FROM THE BOTTOM UP, PROVIDING GUIDELINES THAT ARISE FROM CONSIDERATION OF:
  - MATERIALS PROPERTIES
  - CAPABILITIES AND LIMITATIONS OF EXISTING MANUFACTURING PROCESSES
- SHOWN HEREIN ARE RULES THAT MIGHT GOVERN THE SELECTION AND UTILIZATION OF MEMS AND NANO DEVICES FROM THE TOP DOWN
- VISION IS THAT MERGING OF TOP-DOWN AND BOTTOM-UP RULES WILL ASSIST ASSIMILATION OF MEMS AND NANOTECHNOLOGY INTO SPACECRAFT SYSTEMS

DESIGN RULES (Cont'd)

CATEGORY	SPACECRAFT CLASS APPLICABILITY			RULE/GUIDELINE	MOTIVATION
	I	II	III		
• Telecommunications	x	x	x	• Plan for redundant data transmission and/or redundant Earth receiving stations in conjunction with onboard data analysis and data compression	• Spacecraft downsizing requires smaller antennas, implying higher frequencies to preserve data rate, greater weather sensitivity, and a need for methods to ensure data receipt
• Guidance and Control			x	• Seek system concepts which do not require a star tracker	• Limits to star tracker downsizing preclude spacecraft downsizing
• Information Processing and Control	x	x	x	• Consciously limit scope of on-board software to functions which contribute to end-to-end life cycle cost reduction	• Processor/memory technology advances will enable vastly increased onboard processing capability enabling the development of clever - but costly - onboard software
• Power	x	x	x	• Make maximum utilization of packaging flexibility to store energy in unconventional volumes	• Enable spacecraft downsizing

DESIGN RULES (Cont'd)

CATEGORY	SPACECRAFT CLASS APPLICABILITY			RULE/GUIDELINE	MOTIVATION
	I	II	III		
• Structure/Mechanical Devices/Cabling					
- Structure	x	x	x	• Develop designs deriving substantial structural support from adjacent spacecraft components	• Enable spacecraft mass downsizing
- MEMS Rotating and Sliding Mechanisms	x	x	x	• Expect lubrication and wear considerations to dominate design	• MEMS-scale devices demonstrate both excessive wear and sensitivity to lubricant-caused adhesion due to surface tension
• Propulsion					
- Gaseous/Liquid/ Solid Propellants	x			• For a Class I spacecraft with a 10-cm dia tank, 2000 psia, and 10% max leakage goal over 3 years, favor liquid/solid propellants. Alternatively, to enable use of gaseous propellants, develop new MEMS valves or accept possible unmanageable propellant loss with existing valves	• Required leak rate of 0.3 scc/hr (standard cc/hr) to enable use of gaseous propellants exceeds existing valve capability of 3 scc/hr

DESIGN RULES (Cont'd)

CATEGORY	SPACECRAFT CLASS APPLICABILITY			RULE/GUIDELINE	MOTIVATION
	I	II	III		
• Propulsion (Cont'd)					
- Gaseous/Liquid/ Solid Propellants (Cont'd)		x		• For a Class II spacecraft with a 2.5-cm dia tank, 2000 psia, and 10% max leakage goal over 3 years, avoid gaseous propellants or, alternatively, develop new MEMS valves	• Required leak rate of 4xE-3 scc/hr to enable use of gaseous propellants exceeds existing valve capability of 3 scc/hr
			x	• For a Class III spacecraft with a 0.1-cm dia tank, 2000 psia, and 10% max leakage goal over 3 years, use liquid/solid propellants only. Gaseous propellants are unfeasible	• Required leak rate of 3xE-7 scc/hr to enable use of gaseous propellants unfeasible
- Filters	x	x	x	• Permit violation of conventional wisdom requiring filtration to (i.e., filter ratings) smaller than, and typically one tenth, the valve stroke	• Certain classes of MEMS valves (e.g., magnetorestrictive valves) deliver high sealing forces which may crush contaminants
- Tank Sizing	x	x	x	• Anticipate spacecraft designs with disproportionately large tanks and/or limited ΔV	• Spacecraft downsizing shrinks tank volume significantly faster than tank diameter

DESIGN RULES (Cont'd)

CATEGORY	SPACECRAFT CLASS APPLICABILITY			RULE/GUIDELINE	MOTIVATION
	I	II	III		
• Propulsion (Cont'd) - Nozzle Design		x	x	• Anticipate need to consider use of unconventional nozzle designs to maintain acceptable Isp for MEMS devices	• MEMS-scale flow passages may fill entirely with a viscous boundary layer, resulting in low flow velocities and lower-than-expected Isp
- System Functionality	x	x	x	• Consider impact of non-continuum flow on propulsion system functionality, including valves, filters, and thrusters	• Non-continuum (i.e., free molecular) flow may be experienced by MEMS-scale devices

DESIGN RULES (Cont'd)

CATEGORY	SPACECRAFT CLASS APPLICABILITY			RULE/GUIDELINE	MOTIVATION
	I	II	III		
• Thermal Control	x	x	x	• Expect no change to conventional resource needs: - Sufficient heater power to maintain acceptable element temperatures - Sufficient area to radiate heat	• Needs unaffected by spacecraft downsizing
- Heaters	x	x	x	• Anticipate increased need for heaters and/or absorbing surfaces	• Maintain acceptable element temperatures for expected lower power, more efficient spacecraft elements, particularly during long periods (days to years) of very low power dormancy
- Radiators	x	x	x	• Anticipate enhanced need	• Accommodate heat dissipation during non-dormancy periods when spacecraft loads may exceed dormancy loads by 2-5X

DESIGN RULES (Cont'd)

CATEGORY	SPACECRAFT CLASS APPLICABILITY			RULE/GUIDELINE	MOTIVATION
	I	II	III		
• Sensor	x	x	x	• Anticipate using ultra-small, multifunctional, integrated sensor packages	• Expected availability
• System					
- Size		x	x	• Expect, to first order, required ΔV and optical aperture size to limit system downsizing. Expect, to second order, required data rate to limit system downsizing	• Limited technology options for propulsion subsystem and optical aperture downsizing
	x	x	x	• Plan to accommodate larger than expected MEMS devices	• MEMS packaging required to ensure device integrability and survival in expected handling, launch, and space environments

NEAR-EARTH OBJECT FLYBY SPACECRAFT

- GOAL
  - DESIGN A SPACECRAFT PROVIDING THE SAME CAPABILITY FOR NEAR-EARTH OBJECT FLYBY MISSION AS THE 2ND GENERATION MICROSPACECRAFT DEVELOPED AT JPL IN 1993 BUT DO SO FOR 1 KG/1 L VS. THE 2ND GENERATION MICROSPACECRAFT'S 5.5 KG/11 L
- MISSION
  - NEAR-EARTH OBJECT FLYBY
  - SOLAR RANGE: 0.8-1.2 AU
  - EARTH RANGE: 0-1.6 AU
  - DURATION: 8 MONTHS
- SCIENCE
  - VISIBLE IMAGING, IMAGING SPECTROMETRY
  - ACCOMMODATE TARGET ALBEDOS 0.1-1.0
  - PROVIDE SPECTRAL IMAGES OVER WAVELENGTH RANGE 0.4-2.65 μm
- SPACECRAFT
  - CLASS II (1 KG, 1-5 W, 1 LITER)
  - NO UPLINK
  - NO NUCLEAR FUEL
  - SINGLE STRING, RELIABILITY CLASS C
  - MAKE AGGRESSIVE USE OF NEW TECHNOLOGY TO REDUCE LIFE-CYCLE, SPACECRAFT, LAUNCH, AND OPERATIONS COSTS

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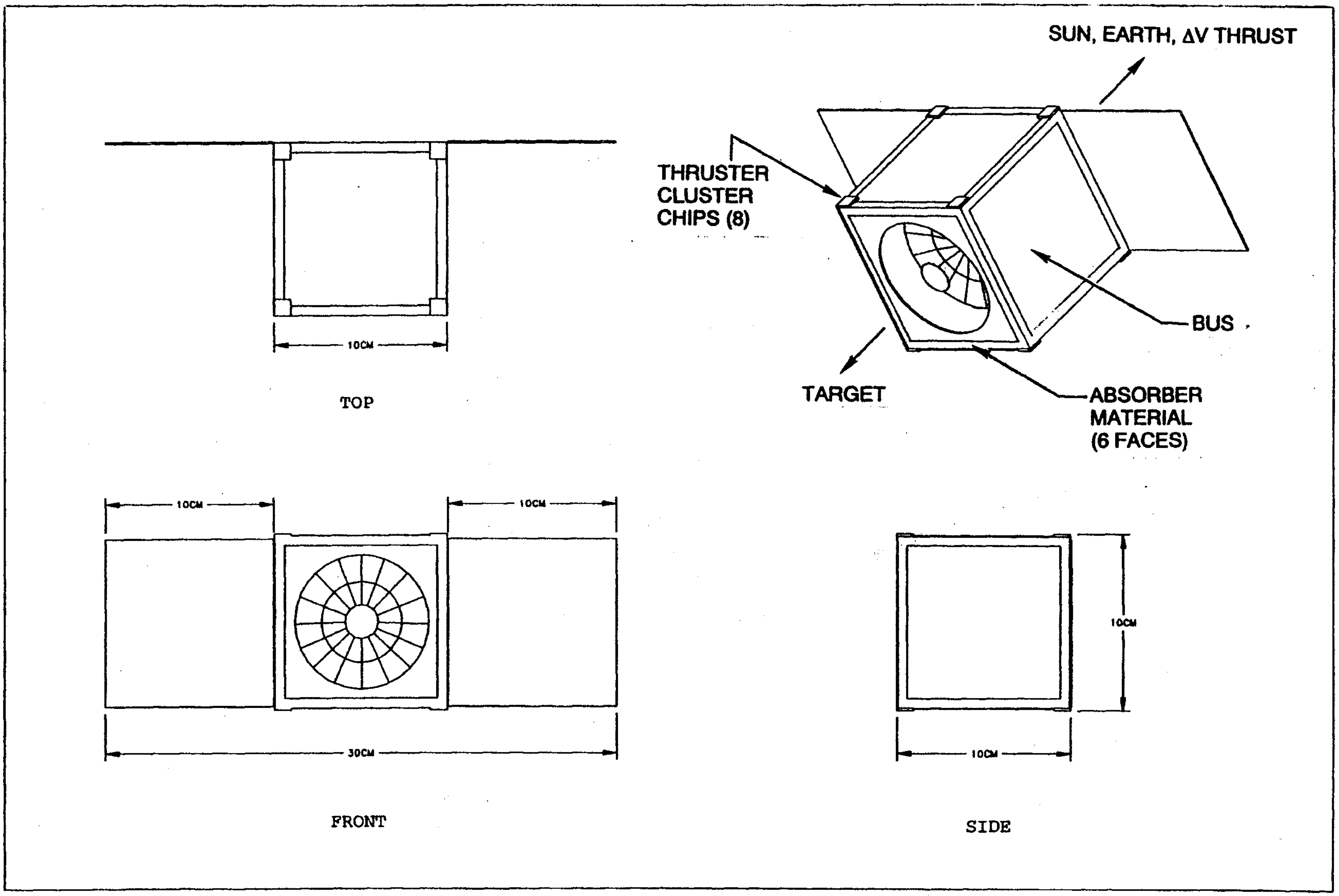
NEAR-EARTH OBJECT FLYBY SPACECRAFT CONFIGURATION



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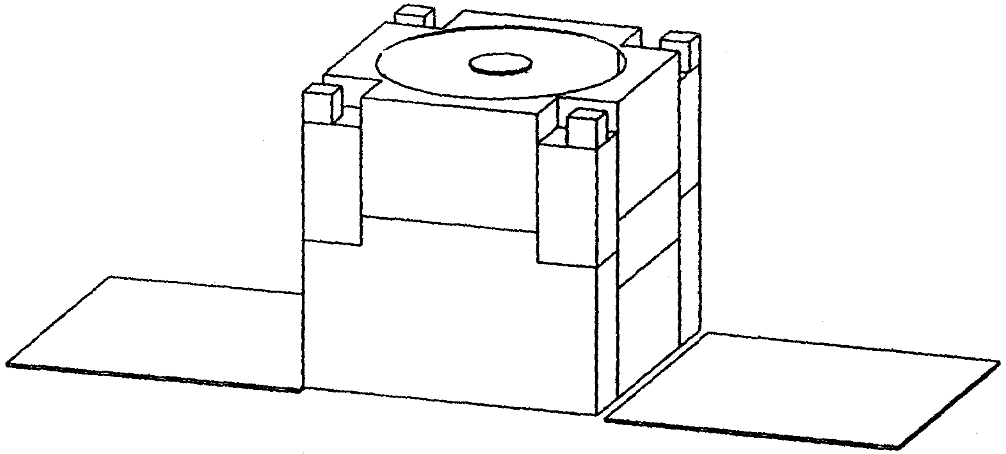
NEAR-EARTH OBJECT FLYBY SPACECRAFT ASSEMBLED CONFIGURATION



NOTES:

1) BUS SHOWN WITH THRUSTER CLUSTER CHIPS/ MLI/MICROLOUVERS/ PRIMARY STRUCTURE REMOVED

2) THIN-FILM PATCH ANTENNA ON BUS SURFACE FACING DOWN

3) ACTIVE SOLAR CELL SURFACE FACING DOWN

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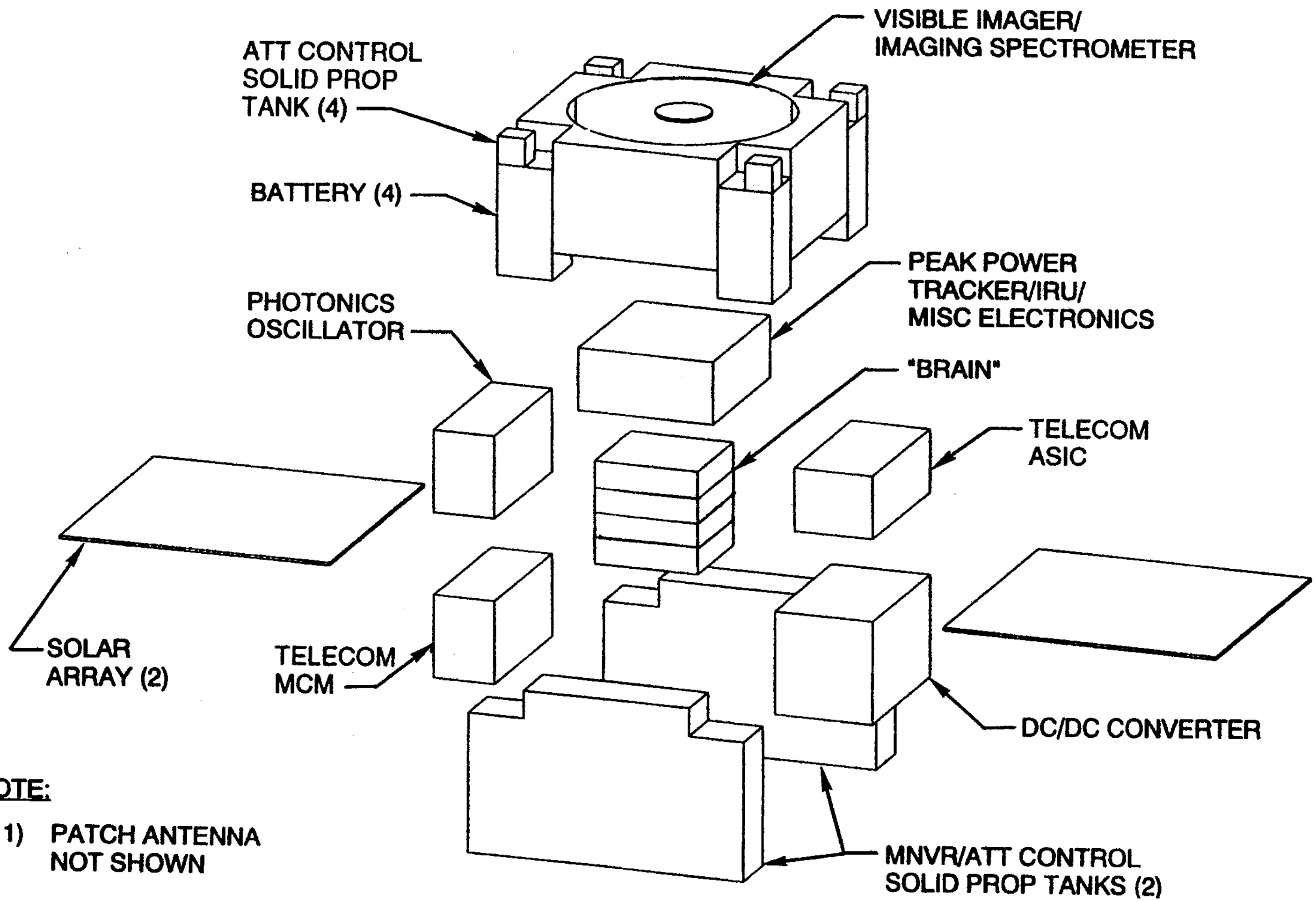
NEAR-EARTH OBJECT FLYBY SPACECRAFT EXPLODED CONFIGURATION



NOTE:

1) PATCH ANTENNA NOT SHOWN

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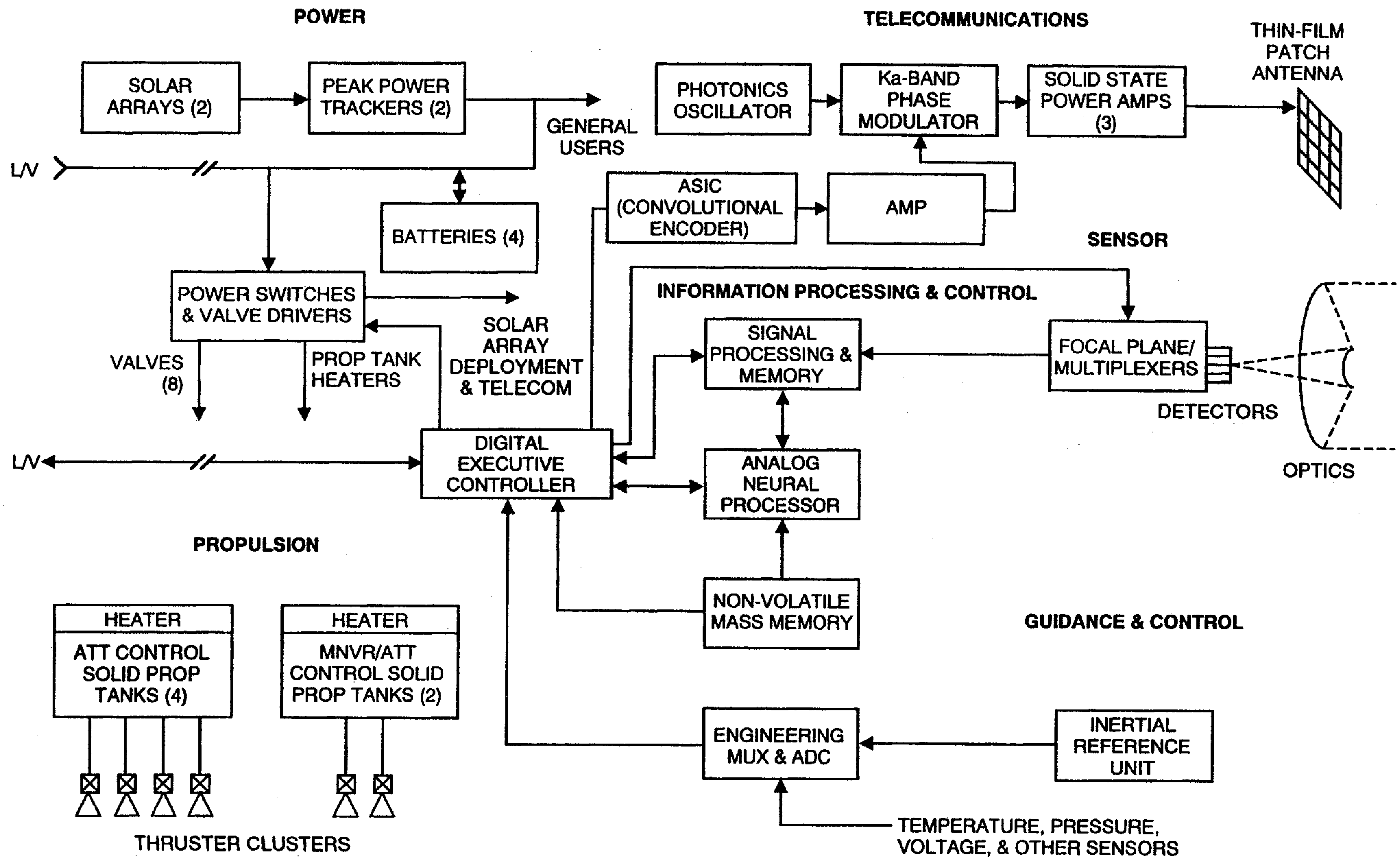
NEAR-EARTH OBJECT FLYBY SPACECRAFT FUNCTIONAL BLOCK DIAGRAM



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NEAR-EARTH OBJECT FLYBY SPACECRAFT MASS AND POWER SUMMARIES

SUBSYSTEM/ELEMENT	MASS, KG	OPERATIONAL MODE POWER, W (avg)		
		CRUISE	DATA ACQ/MNVR/ATT UPDATE	DATA RETURN
		Telecom Off/ Prop Off	Telecom Off/ Prop On	Telecom On/ Prop Off
• Telecommunications	0.246	0	0	2.88
- Photonics Oscillator	0.040			0.10
- MCM	0.040			2.25
• Phase Modulator				
• TLM Amp				
• 1st Ka Amp				
• 2nd Ka Amp				
• 3rd Ka Amp				
- ASIC (Convolutional Encoder)	0.040			0.10
- Patch Antenna	0.047			
- DC/DC Converter (±4, +8 V; 85% efficient)	0.079			0.43
• Guidance and Control	0.040	0.20	0.20	0.20
- IRU	0.040	0.20	0.20	0.20
• Information Processing and Control	0.050	0.80	0.80	0.80
- Brain Modules (4)	0.040	0.50	0.50	0.50
- Engr MUX, ADC	0.001	0.30	0.30	0.30
- Brain Module Interconnects	0.009			

NEAR-EARTH OBJECT FLYBY SPACECRAFT MASS AND POWER SUMMARIES (Cont'd)

SUBSYSTEM/ELEMENT	MASS, KG		OPERATIONAL MODE POWER, W (avg)		
			CRUISE	DATA ACQ/MNVR/ATT UPDATE	DATA RETURN
			Telecom Off/ Prop Off	Telecom Off/ Prop On	Telecom On/ Prop Off
• Power	0.236		0.20	0.20	0.20
- Batteries (4)		0.120			
- Array Solar Cells (23% efficient)		0.026			
- Peak Power Tracker (2)		0.040	0.20	0.20	0.20
- Power Switches (3)/Valve Drivers (8)		0.050			
• Structure/Mechanical Devices/Cabling	0.095		0	0	0
- Structure		0.075			
• Primary					
• Solar Array					
- Mechanical Devices		0.010			
• Array Actuators (2)					
- Cabling		0.010			
• Thermal Control	0.107		0	0	0
- Micro Louvers (150 cm^2)		0.090			
- Coatings (400 cm^2)		0.014			
- MLI (200 cm^2, 5 layers)		0.003			

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NEAR-EARTH OBJECT FLYBY SPACECRAFT MASS AND POWER SUMMARIES (Cont'd)

SUBSYSTEM/ELEMENT	MASS, KG	OPERATIONAL MODE POWER, W (avg)		
		CRUISE	DATA ACQ/MNVR/ATT UPDATE	DATA RETURN
		Telecom Off/ Prop Off	Telecom Off/ Prop On	Telecom On/ Prop Off
• Propulsion (5 mN; 1 mN Thrust/1 W)	0.030	0	5.0 (mnvr) 1.0 (att update)	0
• Sensor	0.181	0.09	0.09	0.09
- Lenses	0.048			
- Lense Support Structure	0.048			
- Focal Plane/Multiplexers	0.050	0.09	0.09	0.09
- Focal Plane Support Structure	0.035			
Subtotal (dry)	0.985	1.29	6.29	4.17
Contingency (20%)	0.197	0.26	1.26	0.83
Subtotal (dry with contingency)	1.182	1.55	7.55	5.0
Propellant	0.160	-	-	-
Total	1.342	1.55	7.55 (mnvr)	5.0

NEAR-EARTH OBJECT FLYBY SPACECRAFT TELECOMMUNICATIONS SUBSYSTEM

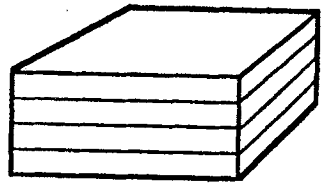
- UTILIZES Ka-BAND. PROVIDES FOR DOWNLINK ONLY
- CONSISTS OF A PHOTONICS OSCILLATOR, KA-BAND PHASE MODULATOR, AND THREE Ka-BAND SOLID STATE AMPLIFIERS TO PRODUCE, MODULATE, AND AMPLIFY THE SIGNAL. RF OUTPUT: 300 mW, 25 dBm
- PROVIDES TELEMETRY CONVOLUTIONAL ENCODING
- PROVIDES DC-DC CONVERSION, AS NECESSARY, TO GENERATE THE REQUIRED ± 4 AND + 8 V VOLTAGES
- RADIATES SIGNAL FROM 9.4 X 9.4 cm THIN-FILM PATCH ANTENNA
- PROVIDES 68 bps DOWNLINK DATA RATE INTO A 34 M HEF DSS AT 1.6 AU (MAX EARTH RANGE)

NEAR-EARTH OBJECT FLYBY SPACECRAFT GUIDANCE AND CONTROL SUBSYSTEM

- PROVIDES 3-AXIS STABILIZATION
- UTILIZES A MICROMACHINED INERTIAL REFERENCE UNIT (IRU) FOR NOMINAL ATTITUDE REFERENCE
- UTILIZES THE SENSOR SUBSYSTEM VISIBLE IMAGER IN THE STAR TRACKER MODE TO UPDATE THE IRU
- FURTHER UTILIZES THE VISIBLE IMAGER FOR TARGET TRACKING DURING ENCOUNTER, WITH IMAGER ACTIVE PIXEL SENSING TECHNOLOGY PERMITTING STAR UPDATES AND SIMULTANEOUS TARGET IMAGING
- CAN ACCOMMODATE A MINI REACTION WHEEL, AT SOME INCREASE IN SPACECRAFT BUS SIZE, TO ACHIEVE THE SLEW RATES (MAX ANGULAR RATE: 11.6 deg/s; MAX ANGULAR ACCELERATION: 1.5 deg/s^2) REQUIRED FOR TARGET BODY TRACKING AND IMAGING SPECTROMETRY DATA ACQUISITION DURING ENCOUNTER SHOULD SUBLIMING SOLID THRUSTER PERFORMANCE PROVE UNACCEPTABLE

NEAR-EARTH OBJECT FLYBY SPACECRAFT INFORMATION PROCESSING AND CONTROL SUBSYSTEM

- UTILIZES MODIFIED 2ND GENERATION MICROSPACECRAFT INFORMATION PROCESSING AND CONTROL "BRAIN" BUILDING BLOCK
- BRAIN BUILDING BLOCK CONSISTS OF FOUR STACKED MODULES EACH CONTAINING TEN 2.5 cm X 2.5 cm X 20 MIL CARRIERS



- MODULES PROVIDE FOR THE FOLLOWING FUNCTIONS AND PERFORMANCE

MODULE	NAME	FUNCTION	PERFORMANCE/CHARACTERISTICS
1	Non-Volatile Mass Memory	Knowledge Base and Archival Data Storage	16 Gbits <0.1 W @ 10 Mbps R/W; 10 gm
2	Analog Neural Processor	Pattern Recognition, Learning, and Optimization	3 GOPS <0.1 W @ 1% duty cycle; 10 gm
3	Digital Executive Controller	Control, Logic, Fuzzy Logic, and Math Processing	100 MIPS 24 Mbytes RAM <0.2 W @ 10 MIPS; 10 gm
4	Signal Processing and Memory	High Speed Processing and Mass Data Storage	600 MFLOPS 3.6 Gbits RAM <0.1 W @ 1% duty cycle; 10 gm

NEAR-EARTH OBJECT FLYBY SPACECRAFT POWER SUBSYSTEM

- UTILIZES SOLAR AND BATTERY POWER
- SOLAR POWER IS PROVIDED BY TWO 10 X 10 cm DUAL/TRIPLE-JUNCTION GaAs ARRAYS WITH 22-26% EFFICIENCY AT 28°C. EACH OF THE TWO 10 X 10 cm ARRAYS PROVIDES 2.0 W BOL FOR A TOTAL OF 4.0 W AT 1.2 AU (MAX SOLAR RANGE). ARRAYS PROVIDE FOR CRUISE OPERATIONS AND BATTERY CHARGING
- BATTERY POWER IS PROVIDED BY FOUR LITiS2 1 AH, RECTANGULAR CROSS SECTION, ≈"AA"-SIZE BATTERIES PROVIDING ≈6 W-H TOTAL AT 75% DOD. BATTERY PROVIDES FOR PROPULSION/TELECOM OPERATION AND LIMITS BUS VOLTAGE SWINGS. BUS IS 4V
- PEAK POWER TRACKER IS UTILIZED TO OPTIMIZE POWER OVER A WIDE RANGE OF ARRAY TEMPERATURES. TRACKER OFFERS UP TO 10-15% NET POWER IMPROVEMENT
- CONTINUOUS POWER IS PROVIDED TO GENERAL USERS, INCLUDING THE "BRAIN." SWITCHED POWER IS PROVIDED FOR TELECOM, SOLAR ARRAY DEPLOYMENT, AND PROPULSION

NEAR-EARTH OBJECT FLYBY SPACECRAFT POWER SUBSYSTEM (Cont'd)

- DESIGN PERMITS ADEQUATE DURATIONS FOR THE THREE REQUIRED OPERATIONAL MODES

MODE	DURATION, hr	POWER SOURCE	COMMENT
• Cruise	Indefinite	Solar Array	-
• Data Acq/Mnvr/ Att Update	0.8	Battery	Accommodates required 0.5 hr encounter target tracking. Requires any maneuver > 0.8 hr (~14 m/s) be segmented.
• Data Return	1.2	Battery	-

NEAR-EARTH OBJECT FLYBY SPACECRAFT STRUCTURAL/MECHANICAL DEVICES/CABLING SUBSYSTEM

- STRUCTURE PROVIDES PRIMARY SUPPORT FOR ALL SPACECRAFT ELEMENTS WITH INDIVIDUAL ELEMENTS DESIGNED TO PROVIDE SUPPORT FOR ADJACENT ELEMENTS
- SOLAR ARRAY SUBSTRATES UTILIZE K-1100 (HIGH THERMAL CONDUCTIVITY COMPOSITE) FACE SHEETS ON AL HONEYCOMB CORE
- SOLE MECHANICAL DEVICES ARE TWO PARAFIN-ACTUATED SOLAR ARRAY DEPLOYMENT DEVICES
- CABLING IS MINIMIZED SINCE MOST BRAIN INTERCONNECTIONS ARE INTERNAL. OTHER INTERCONNECTIONS ARE LOW-MASS CABLING

NEAR-EARTH OBJECT FLYBY SPACECRAFT THERMAL CONTROL SUBSYSTEM

- UTILIZES MICROLOUVERS, SOLAR ABSORBING MATERIALS, PASSIVE RADIATING SURFACES, AND MULTILAYER INSULATION (MLI)

- CONSISTS OF 150 cm^2 OF BUS SIDE/BOTTOM-MOUNTED MICROLOUVERS PLUS 25 cm^2 OF SOLAR ABSORBING MATERIAL IN A 0.6-cm WIDE FRAME ON EACH OF THE SIX BUS FACES

- MICROLOUVERS AND SOLAR ABSORBING MATERIAL PERMIT ACHIEVEMENT OF A 5 – 50°C ENVIRONMENT FOR ELECTRONICS OVER THE REQUIRED SOLAR RANGE OF 0.8 – 1.2 AU AND MIN AND MAX SPACECRAFT POWER LOADS OF ≈1 W AND ≈4+ W, RESPECTIVELY. DESIGN PERMITS INDEFINITE MAINTENANCE OF MIN ELECTRONICS TEMPERATURE FOR WORST-CASE SPACECRAFT ATTITUDES PROVIDING ROBUSTNESS TO SPACECRAFT ATTITUDE LOSS ANOMALIES. ALTERNATIVELY, TO AVOID THERMAL CYCLING OVER THE 5-50°C RANGE AND THE NEED FOR SOLAR ABSORBING MATERIAL, DESIGN COULD INCORPORATE A SWITCHED HEATER

NEAR-EARTH OBJECT FLYBY SPACECRAFT THERMAL CONTROL SUBSYSTEM (Cont'd)

- UTILIZES A SEPARATE, DEDICATED, BUS TOP-MOUNTED 9.4 X 9.4 cm PASSIVE RADIATOR HAVING AN EMISSIVITY OF 0.8 FOR FOCAL PLANE COOLING TO 190 K. RADIATOR PERMITS DISSIPATION OF 0.6 W FOR FOCAL PLANE ELECTRONICS AND PARASITICS
- PROVIDES FOR SOLAR ARRAY COOLING BY PASSIVE RADIATION FROM BOTH ARRAY SIDES
- UTILIZES MLI ON ALL EXPOSED BUS SURFACES NOT COVERED BY LOUVERS, SOLAR ABSORBING MATERIAL, RADIATORS, OR OTHER SPACECRAFT ELEMENTS

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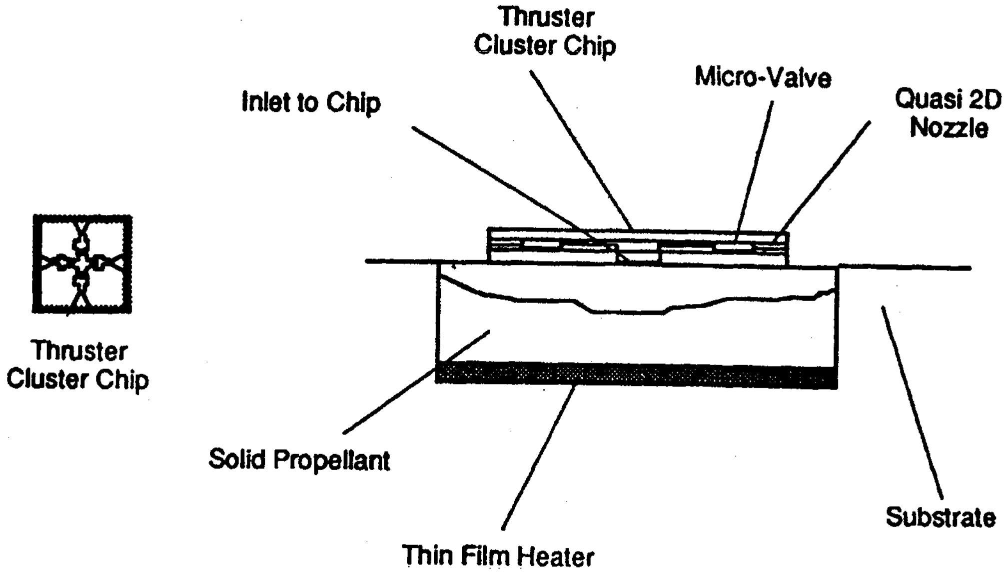
NEAR-EARTH OBJECT FLYBY SPACECRAFT PROPULSION SUBSYSTEM

- UTILIZES SUBLIMING SOLID PROPULSION



- PROVIDES FOR ATTITUDE CONTROL, ΔV MANEUVERS, AND SPACECRAFT SLEWING FOR TARGET TRACKING DURING ENCOUNTER

- OPERATES BY HEATING A SOLID PROPELLANT (e.g., AMMONIUM HYDROSULFIDE, AMMONIA CARBAMATE) INSIDE A CAVITY WHICH RESULTS IN PROPELLANT SUBLIMATION AND GAS EXPANSION THROUGH A NOZZLE TO PRODUCE THRUST. DELIVERS VARIABLE THRUST, 1mN THRUST/2.3-2.8 W INPUT POWER, AND Isp = 50-65 s

NEAR-EARTH OBJECT FLYBY SPACECRAFT PROPULSION SUBSYSTEM (Cont'd)

- CONSISTS OF EIGHT THRUSTER CLUSTERS, WHICH PROVIDE ATTITUDE CONTROL IN COUPLES, AND SIX PROPELLANT TANKS. TOTAL PULSES REQUIRED/THRUSTER: $\leq$ 500

- ANY, OR ALL, OF THE EIGHT THRUSTER CLUSTERS MAY BE USED FOR ATTITUDE CONTROL. FOUR OF THE CLUSTERS ARE CONNECTED TO INDIVIDUAL 1 cm^3 TANKS. DESIGN DELIVERS 1 mN THRUST FOR ATTITUDE UPDATES PERFORMED EVERY 38-40 hrs TO MAINTAIN 1 deg CRUISE DEADBAND

- TWO OF THE EIGHT CLUSTERS PERFORM BOTH ATTITUDE CONTROL AND ΔV FUNCTIONS. EACH OF THESE TWO CLUSTERS IS CONNECTED TO A 120 cm^3 TANK STORING 80 gm OF PROPELLANT. DESIGN PROVIDES 5 mN THRUST (2 X 2.5 mN THRUSTERS OR, ALTERNATIVELY, 4 X 1.25 mN THRUSTERS) TO PERFORM MANEUVERS. DESIGN DELIVERS 100 m/s ΔV. 200 m/s ΔV REQUIRES BUS ENLARGEMENT OR, ALTERNATIVELY, BUS ENLARGEMENT AND A HYDRAZINE SYSTEM

NEAR-EARTH OBJECT FLYBY SPACECRAFT PROPULSION SUBSYSTEM (Cont'd)

- FOUR OF THE CLUSTERS WILL BE USED FOR ENCOUNTER TARGET TRACKING. DESIGN PROVIDES 5 mN THRUST (NOMINALLY 4 X 1.25 mN THRUSTERS) TO ACHIEVE THE REQUIRED SLEW RATES FOR TRACKING. ADDITIONAL CLUSTERS WILL BE UTILIZED DURING ENCOUNTER TO SCAN THE OPTICS FOV ACROSS THE TARGET TO IMPLEMENT THE IMAGING SPECTROMETER FUNCTION

- VALVED AND VALVELESS OPTIONS EXIST, WITH VALVED CONCEPTS PROVIDING SMALLER MIN IMPULSE BIT. USE OF SUBLIMING SOLID PERMITS HIGHLY VOLUME-EFFICIENT PROPELLANT STORAGE USING CUBICAL/RECTANGULAR TANKS DUE TO LOW TANK PROPELLANT SUBLIMATION PRESSURES (7 psia, AMMONIUM HYDROSULFIDE; 2 psia, AMMONIA CARBAMATE)

NEAR-EARTH OBJECT FLYBY SPACECRAFT SENSOR SUBSYSTEM

- UTILIZES UPDATED 2ND GENERATION MICROSPACECRAFT VISIBLE IMAGER AND IMAGING SPECTROMETER
- FUNCTIONS AS NAVIGATION IMAGER, TARGET VISIBLE IMAGER, TARGET IMAGING SPECTROMETER, AND STAR TRACKER FOR ATTITUDE CONTROL IRU UPDATES
- RESPONDS TO STARS OF MAGNITUDE $\leq$ 10 FOR IRU UPDATES AND NAVIGATION. PROVIDES SPECTRAL IMAGES OVER THE WAVELENGTH RANGE 0.4-2.65 μm
- OPTICS ARE ENTIRELY REFLECTING AND CONSTRUCTED OF SiC WITH SiC SUPPORT STRUCTURE. KEY PARAMETERS ARE:
  - FOCAL LENGTH: 2.4 cm
  - APERTURE: 8.0 cm
  - SPEED: f/3.0
  - FOV: 3 deg

NEAR-EARTH OBJECT FLYBY SPACECRAFT SENSOR SUBSYSTEM (Cont'd)

- FOCAL PLANE IS COMPRISED OF A 1024 X 1024 PIXEL (10 X 10 μm PITCH) Si FRAMING ARRAY (0.4-1.0 μm) AND THREE 32 X 512 PIXEL (20 X 20 μm PITCH) IMAGING SPECTROMETER DETECTORS WHICH COMPRISE THE IMAGING SPECTROMETER ARRAY: Si (0.4-0.9 μm); InGaAs (0.9-1.7 μm); InGaAs (1.7-2.65 μm)

- IMAGING SPECTROMETER FUNCTION IS ACHIEVED THROUGH USE OF THREE LINEAR VARIABLE FILTERS POSITIONED ON THE THREE SEPARATE DETECTORS WHICH COMPRISE THE IMAGING SPECTROMETER ARRAY. MULTISPECTRAL IMAGE IS CREATED BY SCANNING THE OPTICS FOV ACROSS THE TARGET AS THE FOCAL PLANE IS REPEATEDLY READ OUT, PERMITTING ALL AREAS OF THE TARGET TO BE VIEWED IN EACH WAVELENGTH INTERVAL PROVIDED BY THE SPECTROMETER

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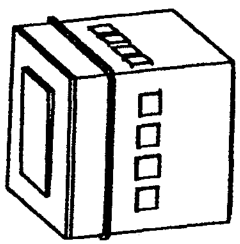
NEAR-EARTH OBJECT FLYBY SPACECRAFT KEY TECHNOLOGY NEEDS AND PRIORITIES

SUBSYSTEM	TECHNOLOGY NEEDS	COMMENT	PRIORITY
• Telecommunications	• Photonics Oscillator	-	• High
	• Ka-Band Phase Modulator	-	• High
	• Thin-Film Patch Antenna	-	• High
• Guidance and Control	• Micromachined IRU	• Drift < 0.1 deg/hr	• High
	• Mini (not Micro) Reaction Wheel	• Potential	• Low
• Information Processing and Control	• 2nd Generation Micro-spacecraft "Brain" Building Block	-	• High
• Power	• Dual/Triple-Junction GaAs Arrays	• 22-26% efficient	• Medium/ High
	• LiTiS2 Batteries	• Rectangular cross section	• High
	• Low Mass Peak Power Tracker	• <25 gm, 80-97% efficient, 2.5 max W out	• Low
	• Low Mass Power Switches/Valve Drivers	• <5 gm	• Medium
• Structure/Mechanical Devices/Cabling	• Advanced Composite Structures	-	• Medium

NEAR-EARTH OBJECT FLYBY SPACECRAFT
KEY TECHNOLOGY NEEDS AND PRIORITIES (Cont'd)

SUBSYSTEM	TECHNOLOGY NEEDS	COMMENT	PRIORITY
• Thermal Control	• Micro Louvers	• <0.2 gm/cm^2 areal density	• Medium
• Propulsion	• Subliming Solid Propulsion	• 1mN thrust/0.05-1.0 W input power • Non-contaminating to optical/thermal control/solar array surfaces	• High
• Sensor	• Highly Aspheric Optics	-	• High
	• SiC Lighweight Optics/Optical Benches	-	• Medium
	• 0.9V CMOS Logic	-	• Low/ Medium
	• Active Pixel Sensors	-	• Medium

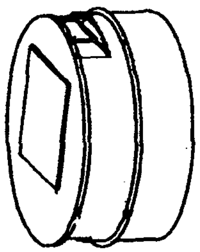
SURFACE CHEMICAL SENSOR



CONCEPT DESCRIPTION

• Class	• III
• Mission and Science Objectives	• Surface chemical sensing using MOX technology • Multiple site survey utilizing multiple, functionally identical, "expendable" sensors surface deployed from carrier mother lander. Sensor data link to lander, overhead orbiter, or rendezvous spacecraft
• Key Design Characteristics	• Size: 3 cm-sided cube • Mass: <200 gm (TBR) • Power: < 0.3 W (TBR) • Data Rate: >100 bps to orbiter, >> 1000 bps to lander • Life: 1-4 hours (TBR) • Features: Omnidirectional S-band link provided by 2 x 2 cm-patch and loop antennas. Battery power. No command. Identical sensors provided on four cube surfaces
• Outlook	• Potentially viable. Requires micro opto-chemical sensor proof of concept, MEMS S-band filter and oscillator development
• Key Technology Needs	• MEMS S-band (3 GHz) telecom filters and oscillators • Conformal-coated batteries • Micro opto-chemical sensors • Thin-film patch antenna

FREE-FLYING GAS SENSOR



CONCEPT DESCRIPTION	
• Class	• III
• Mission and Science Objectives	• Atmospheric/cometary gas sensing using MOX technology • Multiple, functionally identical, "expendable" sensors deployed from mother spacecraft. Sensor data link to carrier spacecraft
• Key Design Characteristics	• Size: 3-cm dia x 2 cm long cylinder • Mass: <200 gm (TBR) • Power: <0.3 W (TBR) • Data Rate: >>1000 bps to carrier spacecraft • Life: 1-4 hours (TBR) • Features: Omnidirectional S-band link provided by 2 x 2-cm patch and loop antennas. Battery powered. No command.
• Outlook	• Same as Surface Chemical Sensor
• Key Technology Needs	• Same as Surface Chemical Sensor

MANEUVERABLE GAS SENSOR

(CONCEPT TBD)

CONCEPT DESCRIPTION	
• Class	• III
• Mission and Science Objectives	• Same as Free-Flying Gas Sensor
• Key Design Characteristics	• Size: 3-cm+ dia x 2-cm+ long cylinder • Mass: <250 gm (TBR) • Power: <0.4 W (TBR) • Data Rate: >>1000 bps to carrier spacecraft • Life: 1-4 hours (TBR) • Features: Same as Free-Flying Gas Sensor, plus maneuverability provided by subliming solid thrusters
• Outlook	• Viability uncertain. Requires same technology proof of concept/development as Free-Flying Gas Sensor, plus micro star tracker for which no viable concept of the required size has been identified
• Key Technology Needs	• Same as Surface Chemical Sensor PLUS • Subliming solid thrusters • Doped Si isolation valve • Micro star tracker

CONCLUSIONS

- MEMS PROMISE IS GREATEST IN CLASS III APPLICATIONS WHERE MASS/SIZE ADVANTAGES ARE POTENTIALLY ENABLING FOR NEW CONCEPTS, PARTICULARLY SENSORS
- ADDITIONAL EXCELLENT, IMMEDIATELY USEFUL APPLICATIONS OF MEMS IN SPACECRAFT SYSTEM/SUBSYSTEM DESIGN INCLUDE:
  - INERTIAL REFERENCE UNITS (IRU)
  - MICROPROPULSION/MICROVALVES
  - TELECOMMUNICATIONS FILTERS AND OSCILLATORS
- INTEGRATION OF SELECTED MEMS/NANOTECHNOLOGIES AND OTHER NEW TECHNOLOGIES OFFERS THE BEST PROMISE OF ACHIEVING THE NEW GENERATION OF ULTRA-SMALL SPACECRAFT
- A 1 kg-SPACECRAFT CONCEPT FOR A NEAR-EARTH OBJECT FLYBY MISSION EXISTS NOW

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PARTICIPANTS IN THE EFFORT INCLUDED:

W. ARENS
J. BRADLEY
D. COLLINS
C. ENGELBRECHT
T. GEORGE
R. GARCIA
G. HARVEY
M. HERMAN
R. HORTTOR
C. KYRIACOU
J. MCGUIRE
J. MUELLER
D. RASCOE
H. SMITH
A. VAISNYS